

# Radio to TeV radiation initiated by termination of hadronic jets from microquasars in the ISM

V. Bosch-Ramon<sup>\*</sup>, F. A. Aharonian<sup>†</sup> and J.M. Paredes<sup>\*</sup>

<sup>\*</sup>*Departament d'Astronomia i Meteorologia, Universitat de Barcelona, Av. Diagonal 647, E-08028 Barcelona, Catalonia, Spain*

<sup>†</sup>*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, Heidelberg, 69117, Germany*

**Abstract.** Microquasars (MQs) are potential candidates to produce a non-negligible fraction of the observed galactic cosmic rays. The protons accelerated at the jet termination shock interact with the interstellar medium and may produce extended emission detectable at different energy bands through several processes: neutral pion-decay produce high-energy and very high-energy gamma-rays, secondary electrons produced by charged pion-decay generate synchrotron and bremsstrahlung emission. In addition, the jets of MQs themselves are likely sources of gamma-rays. We discuss about the association between the intrinsic and the indirect emission coming from these objects.

**Keywords:** X-ray binaries, gamma-ray sources

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## INTRODUCTION

MQs are X-ray binary systems with relativistic jets or outflows emitting non-thermal radio emission ([1]). Although the mechanisms of jet generation are still under discussion ([2]), it is known that these outflows are magnetized, and they contain and likely accelerate relativistic particles that produce the observed extended radio structures. Moreover, the radio band seems to be not the only energy range which these jets emit at. The likely association between MQs and gamma-ray sources based on observational (for LS 5039, see [3] and [4]; for LS I +61 303, see [5]) and theoretical grounds ([6], [7], [8]) point strongly to these objects as very high energy cosmic ray accelerators, not only of leptons, but perhaps also of hadrons ([9], [10]).

If relativistic hadrons leave the region of acceleration, they can interact further away with high density regions of the ISM (e.g. clouds), and the electromagnetic spectrum generated in such interactions would present features depending on the propagation effects ([11]) linked to the diffusive medium as well as on the properties of the cloud and the jet itself. We have explored here which consequences in the observed spectrum, as well as concerning the gamma-ray imaging, would arise from a region where a gamma-ray emitting microquasar jet is interacting with a nearby cloud.

## EMISSION FROM REGIONS CONTAINING MQ AND CLOUDS

We assume that a significant amount of protons, accelerated in the region where the jet ends, are released interacting further away with the ISM (see [12]). These protons diffuse through the ISM with a diffusion coefficient homogenous in spaces that follows a power-

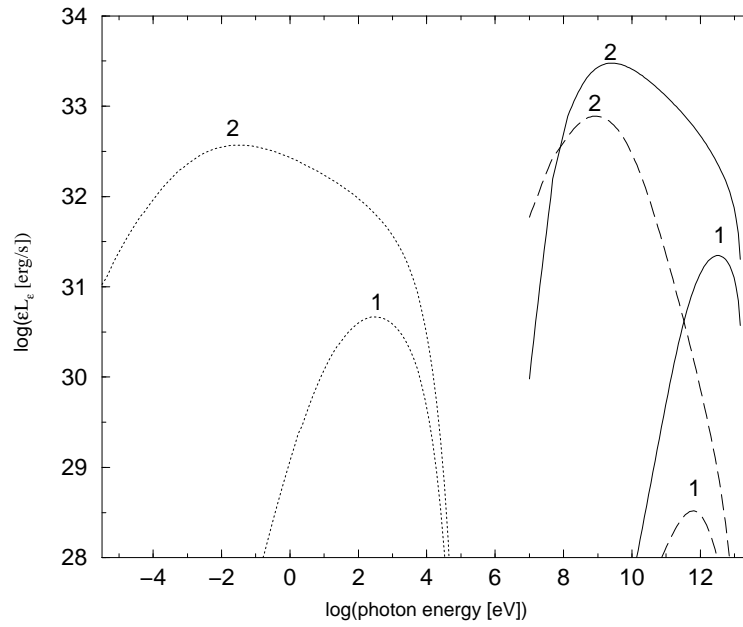
**TABLE 1.** Adopted parameter values

Parameter	Value
diffusion coefficient normalization constant at 10 GeV	$10^{27} \text{ cm}^2 \text{ s}^{-1}$
diffusion power-law index	0.5
ISM medium density	$0.1 \text{ cm}^{-3}$
cloud density	$10^4 \text{ cm}^{-3}$
mass of the high density region/cloud	$3 \times 10^4 M_{\odot}$
magnetic field within the cloud	$5 \times 10^{-4} \text{ G}$
IR radiation energy density within the cloud	$10 \text{ eV cm}^{-3}$
power-law index of the high energy protons	2
maximum energy of the high energy protons	$10^5 \text{ GeV}$
kinetic luminosity of accelerated protons in the MQ jet	$10^{37} \text{ erg s}^{-1}$
kinetic energy of accelerated protons in the impulsive ejection	$10^{48} \text{ erg}$
distance between the MQ and the cloud	10 pc

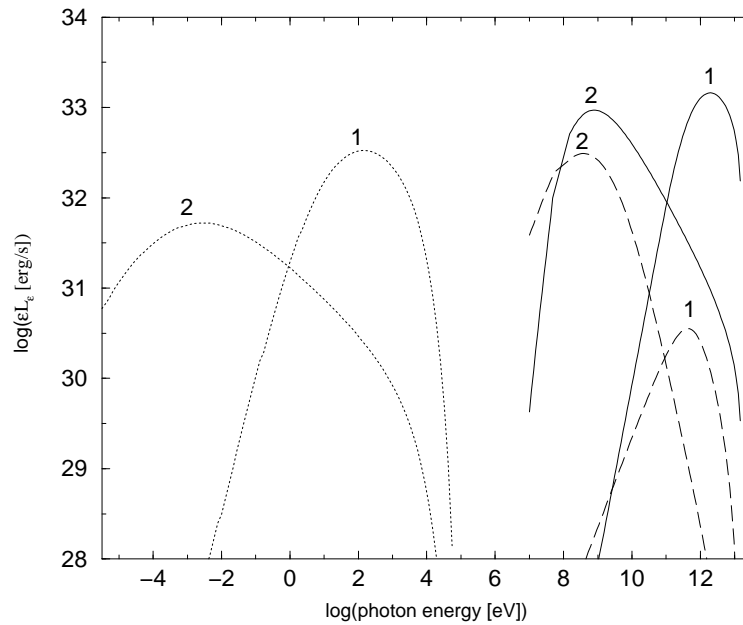
law in energy. Due to propagation effects, the outcomes of the interactions between the protons released from the jet and cloud hydrogen nuclei can differ strongly depending on the age, the nature (impulsive or continuous) of the accelerator and the distance between this and the cloud. The proton-proton collisions within the cloud lead to the creation of neutral and charged pions. Then, neutral pions will decay to gamma-ray photons while charged pions will decay to  $e^-$  and  $e^+$ . These secondary particles can produce significant levels of synchrotron (from radio frequencies to X-rays) and Bremsstrahlung emission (from soft gamma-rays to TeV range), and generally with much less efficiency, inverse Compton emission through interaction with the ambient infrared photons. In Table 1, we present parameter values adopted concerning relevant physical quantities for a middle size molecular cloud, the ISM and a jet of a MQ. Also, in Figs. 1 and 2, we show the computed broad-band spectral energy distribution (SED) of the radiation coming from the bombarded cloud for the continuous and the impulsive case respectively.

## DISCUSSION

From the figures shown in the previous section, it is seen that a cloud interacting with the cosmic rays released from jet of a MQ could be detected by ground-based cherenkov telescopes, and the same applies at high-energy gamma-rays for satellite-borne instruments. However, as noted above, MQs are also intrinsic sources of very high-energy gamma-rays, detected already at TeV energies, and likely sources of high-energy gamma-rays. Theoretical studies show also that jets could be emitting emission in the whole spectral range ([13]). This implies that these objects, when observed with good sensitivity and angular resolution instruments, could appear as compact sources with nearby extended hot spots, being the spectra of both related to each other and to the separation distance and age and nature of the accelerator. The discovery of such double sources would provide of information about the physical properties of the clouds and the MQs themselves. For instance, it would be possible to estimate the magnetic field and hydrogen density in the cloud, the magnetic field, the accelerated particle spectrum and the relativistic hadronic content in the jet, and finally the diffusion coefficient of the



**FIGURE 1.** SED for a continuous MQ from radio to very high-energy gamma-rays at two different ages:  $t=100$  yr (1),  $t=10000$  yr (2). It is plotted the neutral pion-decay gamma-rays (solid line), Bremsstrahlung (dashed line) and synchrotron emission (dotted line).



**FIGURE 2.** The same as in Fig. 1, but for an impulsive microquasar.

ISM.

## SUMMARY

We have shown that jets of MQs can indirectly generate broad-band emission up to very high energies through interactions between their hadronic content, accelerated in and released from the jet, and the hydrogen nuclei of nearby molecular clouds. Due to the intrinsic nature of these objects as gamma-ray emitters, the new ground-based Cherenkov telescopes and satellite-borne gamma-ray instruments could detect double sources in their fields of view: the MQ itself and the jet proton bombarded high density ISM.

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